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# A critical review on convective heat transfer correlations of nanofluids

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ABSTRACT

Nanofluids are engineered colloids made of a base fluid and nanoparticles, which become potential candidate for next generation heat transfer medium. Nanofluids have higher thermal conductivity and single-phase heat transfer coefficients than their base fluids. The heat transfer coefficient increases appear to go beyond the mere thermal conductivity effect, and cannot be predicted by traditional pure fluid correlations. This review summarizes the correlations development for fluid flow and heat transfer characteristics of nanofluids in forced and free convection flows. The review shows that most of the investigations recommended conventional friction factor correlation of base fluid for pressure drop prediction of the nanofluids for both laminar and turbulent flows in minichannel as well as in microchannel. However, the conventional correlation is not suitable for heat transfer coefficient of nanofluid and hence various correlations have been suggested for the Nusselt number for both laminar and turbulent flow. However, the large deviation of predicted values for proposed correlations has been observed may be due to strong influence of particle properties and nanofluid composition on flow and heat transfer characteristics, lack of common understanding on basic mechanism of nanofluid flow and insufficient experimental data on nanofluid heat transfer. Hence, a general framework for heat transfer correlation needs to be developed.



**Contents**



## 1. Introduction

Nanofluids, coined by Choi [1], are a new class of nanotechnology-based heat transfer fluids that are engineered by stably suspending a small amount of particles, fibers, or tubes with dimension on the order of 1–100 nm. Nanofluids consisting of such particles suspended in liquids (typically conventional heat transfer liquids) have been shown to enhance the thermal conductivity and convective heat transfer performance of the base liquids. The thermal conductivities of the particle materials are typically an order-of-magnitude higher than those of the base fluids such as water, ethylene glycol, and light oils (Table 1), and nanofluids, even at low volume concentrations, resulting in significant increases in thermal performance [2–9]. Nanofluids have the potential to reduce such thermal resistances, and the industrial groups that would benefit from such improved heat transfer fluids are quite varied. They include transportation (coolant, fuel, and oil), electronics, medical (Nanodrug delivery, Cancer Theraupetics, Cryopreservation, Nanocryosurgery, Sensing and Imaging), food, defense, nuclear, space and manufacturing of many types [10].

The nanofluid does not mean a simple mixture of solid particles and base fluid. In order to prepare the nanofluids by dispersing the nanoparticles in a base fluid, proper mixing and stabilization of the particles is required. Normally, there are three effective methods used to attain stability of the suspension against sedimentation of the nanoparticles, which are summarized as follows: (1) control

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**Nomenclature**

| | |
|---|---|
| $c_p$ | specific heat capacity |
| $d$ | diameter (m) |
| $D$ | tube inner diameter (m) |
| $f$ | Darcy friction factor |
| $k$ | thermal conductivity (W m$^{-1}$ K$^{-1}$) |
| $L$ | tube length (m) |
| $Nu$ | Nusselt number |
| $Pe$ | Peclet number |
| $Pr$ | Prandtl number |
| $q''$ | heat flux (W m$^{-2}$) |
| $Ra$ | Rayleigh number |
| $Re$ | Reynolds number |
| $x$ | tube entrance length (m) |
| $\alpha$ | thermal diffusivity (m$^2$ s$^{-1}$) |
| $\beta$ | volumetric thermal expansion coefficient |
| $\mu$ | dynamic viscosity (kg m$^{-1}$ s$^{-1}$) |
| $\phi$ | particle volume concentration |
| $\rho$ | fluid density (kg m$^{-3}$) |

*Subscripts*

| | |
|---|---|
| $b$ | bulk |
| $bf$ | base fluid |
| $nf$ | nanofluids |
| $p$ | nano particle |
| $w$ | wall |

of the ph value of the suspensions, (2) addition of surface activators or surfactants and (3) use of ultrasonic vibration. All of these techniques aim at changing the surface properties of the suspended nanoparticles and suppressing the formation of clusters of particles in order to obtain stable suspensions. Compared to conventional solid–liquid suspensions for heat transfer intensifications, properly engineered nanofluids possess the following advantages [9]:

- High specific surface area and therefore more heat transfer surface between particles and fluids.
- High dispersion stability with predominant Brownian motion of particles.
- Reduced pumping power as compared to pure liquid to achieve equivalent heat transfer intensification.
- Reduced particle clogging as compared to convention slurries, thus promoting system miniaturization.
- Adjustable properties, including thermal conductivity and surface wettability, by varying particle concentrations to suit different applications.

**Table 1**
Specific heat capacity and thermal conductivity.

| Materials | Specific heat (kJ/kg K) | Thermal conductivity (W/m K) |
|---|---|---|
| Diamond | 0.509 | 3300 |
| Carbon nanotube | – | 3000 |
| Silver (Ag) | 0.235 | 429 |
| Copper (Cu) | 0.385 | 401 |
| Silicon carbide (SiC) | 1.340 | 350 |
| Titanium carbide (TiC) | 0.711 | 330 |
| Gold (Au) | 0.129 | 317 |
| Aluminum nitride (AlN) | 0.740 | 285 |
| Aluminum (Al) | 0.904 | 237 |
| Silicon (Si) | 0.714 | 148 |
| Graphite | 0.701 | 120 |
| Sodium (Na) | 1.230 | 72.3 |
| Alumina ($Al_2O_3$) | 0.773 | 40 |
| Copper oxide (CuO) | 0.551 | 32.9 |
| Titanium dioxide ($TiO_2$) | 0.692 | 8.4 |
| Zirconia | 0.418 | |
| Water (base fluid) | 4.187 | 0.613 |

The heat transfer enhancement using nanofluids may be affected by several factors such as gravity, Brownian motion, Brownian diffusion, friction force between the fluid and nanoparticles, sedimentation, dispersion, layering at the solid/liquid interface, ballistic phonon transport and thermophoresis may coexist in the main flow of a nanofluid. Experiments showed that thermal conductivity increase is not the sole reason for heat transfer enhancement in nanofluids. Other factors, discussed above, may play role in heat transfer augmentation due to nanoparticles. Particle fluctuations and interactions, especially in high Peclet number may cause the change in flow structure and lead to augmented heat transfer due to the presence of nanoparticles. However, the proper physical mechanism of heat transfer enhancement has not been established till date. It is clear that the increase of thermal conductivity might be offset by the increase of viscosity, the decrease of effective specific heat of nanofluid. However, experiments showed significant heat transfer enhancement with little penalty of pressure drop.

Because of the effects of several factors, the heat characteristics of nanofluids are dependent on the properties of the base liquid and the dispersed phases, particle concentration, size and morphology, as well as the presence of dispersants or surfactants. Therefore, the general form of the Nusselt number yields [11],

$$Nu_{nf} = f\left(Re, Pr, \frac{k_p}{k_{bf}}, \frac{(\rho c_p)_p}{(\rho c_p)_{bf}}, \phi, \text{particle size and shape, flow structure}\right) \tag{1}$$

In the present study, I present a critical review on proposed heat transfer and pressure drop correlations of nanofluid followed by comparison of correlations.

## 2. Nanofluid properties and nondimentional numbers

Using classical formulas derived for a two-phase mixture, the density, specific heat capacity and thermal expansion coefficient of the nanofluid under consideration as a function of the particle volume concentration and individual properties can be computed using following equations, respectively:

$$\rho_{nf} = (1-\phi)\rho_{bf} + \phi\rho_p \tag{2}$$

$$(\rho c_p)_{nf} = (1-\phi)(\rho c_p)_{bf} + \phi(\rho c_p)_p \tag{3}$$

$$(\rho\beta)_{nf} = (1-\phi)(\rho\beta)_{bf} + \phi(\rho\beta)_p \tag{4}$$

However, the transport properties of nanofluid: dynamic viscosity and thermal conductivity are not only dependent on volume fraction of nanoparticle, also highly dependent on other parameters such as particle shape (spherical, disk shape or cylindrical), size, mixture combinations and slip mechanisms, surfactant, etc. Studies showed that the viscosity as well as thermal conductivity both increases by use of nanofluid compared to base fluid. So far, various theoretical and experimental studies have been conducted and various correlations have been proposed for dynamic viscosity and thermal conductivity of nanofluids. However, any general correlations have not been established due to lack of common understanding on mechanism of nanofluid.

For the correlations, the following dimensionless governing parameters, namely the Reynolds, Prandtl, Grashof, Rayleigh and Peclet numbers, are introduced:

$$Re = \frac{\rho u_m D}{\mu} \tag{5}$$

$$Pr = \frac{c_p \mu}{k} \tag{6}$$

$$Gr = \frac{\rho^2 g \beta q'' D^4}{k \mu^2} \tag{7}$$

$$Ra = \frac{\rho g \beta q'' D^4}{\alpha \mu k} \tag{8}$$

$$Pe_d = \frac{u_m d_p}{\alpha} \tag{9}$$

where the thermal diffusivity of nanofluid is given by,

$$\alpha_{nf} = \frac{k_{nf}}{(\rho c_p)_{nf}} = \frac{k_{nf}}{(1-\phi)(\rho c_p)_{bf} + \phi(\rho c_p)_p} \tag{10}$$

## 3. Forced convective heat transfer of nanofluids

Pak and Cho [12] experimentally investigated the turbulent friction and convective heat transfer behaviors of water based nanofluids heated with constant heat flux boundary condition in circular stainless steel tube of 10.66 mm inner diameter and 4.8 m length. Two different metallic oxide particles, γ-alumina ($Al_2O_3$) and titanium dioxide ($TiO_2$) with mean diameters of 13 and 27 nm, respectively, were used as suspended particles. They observed that, the Nusselt number of the dispersed fluids for fully developed turbulent flow increased with increasing volume concentration as well as the Reynolds number. However, it was found that the convective heat transfer coefficient of the dispersed fluid at a volume concentration of 3% was 12% smaller than that of pure water when compared under the condition of constant average velocity. Therefore, better selection of particles having higher thermal conductivity and larger size was recommended in order to utilize dispersed fluids as a working medium to enhance heat transfer performance. The experimental heat transfer coefficient values were more than predicted from conventional correlation. Hence, the following correlation was suggested for volume concentration of 0–3%, Reynolds and Prandtl numbers of $10^4$ to $10^5$ and 6.5–12.3, respectively:

$$Nu_{nf} = 0.021 Re_{nf}^{0.8} Pr_{nf}^{0.5} \tag{11}$$

Li and Xuan [13] experimentally investigated the convective heat transfer and flow characteristics of the Cu–$H_2O$ nanofluid under laminar flow in a straight brass tube of the inner diameter of 10 mm and the length of 800 mm. The effects of the volume fraction of suspended nanoparticles and the Reynolds number on the heat transfer and flow characteristics were observed. The experimental results showed that the suspended nanoparticles remarkably increase the convective heat transfer coefficient of the base fluid and the nanofluid has larger heat transfer coefficient than pure water under the same Reynolds number. Compared with the base fluid, for example, the convective heat transfer coefficient is increased about 60% for the nanofluid with 2.0 vol.% Cu nanoparticles at the same Reynolds number. The heat transfer feature of a nanofluid increases with the volume fraction of nanoparticles. Considering some factors affecting convective heat transfer characteristics of nanofluids, such as the flow velocity, the transport properties, the volume fraction of nanoparticle, the microconvective and microdiffusion of the nanoparticles, a new convective heat transfer correlation for nanofluid suspending the nanoparticles under single-phase flows had been established. Comparison between the experimental data and the calculated results indicate that the correlation describes correctly the energy transport of the nanofluid. The suggested correlation for volume concentration of 0–2% and minimum *Re* of 800:

$$Nu_{nf} = 0.4328(1 + 11.258\phi^{0.754} Pe_p{}^{0.218}) Re_{nf}^{0.333} Pr_{nf}^{0.4} \tag{12}$$

Xuan and Li [14] also experimentally investigated the convective heat transfer and turbulent flow features of the Cu-$H_2O$ nanofluid in a straight brass tube of the inner diameter of 10 mm and the length of 800 mm. Result showed that the suspended nanoparticles remarkably enhance heat transfer process and the nanofluid has larger heat transfer coefficient than that of the original base liquid under the same Reynolds number. The heat transfer feature of a nanofluid increases with the volume fraction of nanoparticles. By considering the microconvection and microdiffusion effects of the suspended nanoparticles, they have also proposed the following convective heat transfer correlation for turbulent flow of nanofluids in a tube for volume concentration of 0–2% and Reynolds numbers of $1 \times 10^4$ to $2.5 \times 10^4$:

$$Nu_{nf} = 0.0059(1 + 7.6286\phi^{0.6886} Pe_p{}^{0.001}) Re_{nf}^{0.9238} Pr_{nf}^{0.4} \tag{13}$$

Yang et al. [15] experimentally investigated the convective heat transfer of Graphite-synthetic oil nanofluid under laminar flow in a horizontal tube heat exchanger with aspect ratios significantly different from one (≈0.02). They showed that the graphite nanoparticles increased the static thermal conductivities of the fluid significantly at low weight fraction loadings. However, the experimental heat transfer coefficients showed lower increases than predicted by either the conventional heat transfer correlations for homogeneous fluids, or the correlations developed from the particle suspensions with aspect ratios close to one (Li and Xuan, Eq. (12)). This is due to the fact that spherical Cu nanoparticle was used by Li and Xuan [13] whereas the disk type graphite nanoparticle was used by the authors [15]. They concluded that the type of nanoparticles, particle loading, base fluid chemistry, and process temperature are all important factors to be considered while developing nanofluids for high heat transfer coefficients. The following correlation was proposed for concentration up to 2% and Reynolds number of 5–110:

$$Nu_{nf} = a Re_{nf}^{b} Pr_{nf}^{1/3} \left(\frac{D}{L}\right)^{1/3} \left(\frac{\mu_w}{\mu_b}\right)^{-0.14} \tag{14}$$

where the values of coefficients a and b are dependent on nanofluid compositions and temperature [15].

Maïga et al. [16] numerically investigated the laminar forced convection heat transfer behavior of water–$\gamma Al_2O_3$ and ethylene glycol–$\gamma Al_2O_3$ nanofluids in uniformly heated tube. Their study clearly showed that the inclusion of nanoparticles into the base fluids has produced a considerable augmentation of the heat transfer coefficient that clearly increases with an increase of the particle concentration. However, the presence of such particles has also induced drastic effects on the wall shear stress that increases appreciably with the particle loading. Among the mixtures studied, the ethylene glycol–$\gamma Al_2O_3$ nanofluid appears to offer a better heat transfer enhancement than water–$\gamma Al_2O_3$; it was also the one that has induced more pronounced adverse effects on the wall shear stress. For the case of tube flow, results have also shown that, in general, the heat transfer enhancement also increases considerably with an augmentation of the flow Reynolds number. From the numerical results, the following correlations have been proposed for computing the averaged Nusselt number for the nanofluids considered for both the thermal boundary conditions, valid for $Re \le 1000$, $6 \le Pr \le 753$ and $\phi \le 10\%$:

$$Nu_{nf} = 0.086 Re_{nf}^{0.55} Pr_{nf}^{0.5} \quad \text{for constant wall heat flux} \tag{15}$$

$$Nu_{nf} = 0.28Re_{nf}^{0.35}Pr_{nf}^{0.36} \quad \text{for constant wall temperature} \tag{16}$$

Maïga et al. [17] studied the hydrodynamic and thermal behavior of turbulent flow in a tube using $Al_2O_3$ nanoparticle suspension at various concentrations under the constant heat flux boundary condition. Assuming single-phase model, governing equations were solved by a numerical method of control volume. The following correlation was proposed to calculate the heat transfer coefficient in terms of the Reynolds and the Prandtl numbers, valid for $10^4 \le Re \le 5 \times 10^5$, $6.6 \le Pr \le 13.9$ and $0 < \phi < 10\%$:

$$Nu_{nf} = 0.085Re_{nf}^{0.71}Pr_{nf}^{0.35} \tag{17}$$

Buongiorno [18] explained the abnormal convective heat transfer enhancement observed in nanofluids based on analytical study. He has considered seven slip mechanisms that can produce a relative velocity between the nanoparticles and the base fluid. These are inertia, Brownian diffusion, thermophoresis, diffusiophoresis, Magnus effect, fluid drainage, and gravity. He concluded that, of these seven, only Brownian diffusion and thermophoresis are important slip mechanisms in nanofluids. Considering these two slip mechanisms, he developed a general two-component four-equation nonhomogeneous equilibrium model for mass, momentum, and heat transport in nanofluids. A nondimensional analysis of the equations suggested that energy transfer by nanoparticle dispersion is negligible, and thus cannot explain the abnormal heat transfer coefficient increases. Furthermore, a comparison of the nanoparticle and turbulent eddy time and length scales clearly indicates that the nanoparticles move homogeneously with the fluid in the presence of turbulent eddies, so an effect on turbulence intensity is also doubtful. Thus, he proposed an alternative explanation for the abnormal heat transfer coefficient increment: the nanofluid properties may vary significantly within the boundary layer because of the effect of the temperature gradient and thermophoresis. For a heated fluid, these effects can result in a significant decrease of viscosity within the boundary layer, thus leading to heat transfer enhancement. He proposed a new correlation structure that captures these effects for turbulent flow, given by,

$$Nu_{nf} = \frac{(f/8)(Re_{nf} - 1000)Pr_{nf}}{1 + \delta_v^+(f/8)^{1/2}(Pr_v^{2/3} - 1)} \tag{18}$$

where the dimensionless thickness of laminar sublayer $\delta_v^+$ is an empirical parameter (value can be taken as 15.5 [18]) and $f$ can be calculated by traditional friction factor correlation for turbulent flow.

Anoop et al. [19] carried out experimental investigation on the convective heat transfer characteristics in the developing region of tube flow with constant heat flux with alumina–water nanofluids. The primary objective was to evaluate the effect of particle size on convective heat transfer in laminar developing region. Two particle sizes were used, one with average particle size off 45 nm and the other with 150 nm. They observed that in the developing region, both nanofluids showed higher heat transfer characteristics than the base fluid and the nanofluid with 45 nm particles showed higher heat transfer coefficient than that with 150 nm particles. With increase in particle concentration and flow rate the average heat transfer coefficient value was increased. It was also observed that in the developing region, the heat transfer coefficients show higher enhancement than in the developed region due to property variation in this region due to stronger temperature gradient along with the possibility of larger particle migration effect with lower particle sizes. Based on the experimental results, they have proposed a new correlation, valid in the developing region $50 < x/D < 200$ for laminar flow with $500 < Re < 2000$, given by,

$$Nu_x = 4.36 + [ax_+^{-b}(1+\phi^c)\exp^{-dx_+}][1 + e(d_p/d_{ref})^{-f}] \tag{19}$$

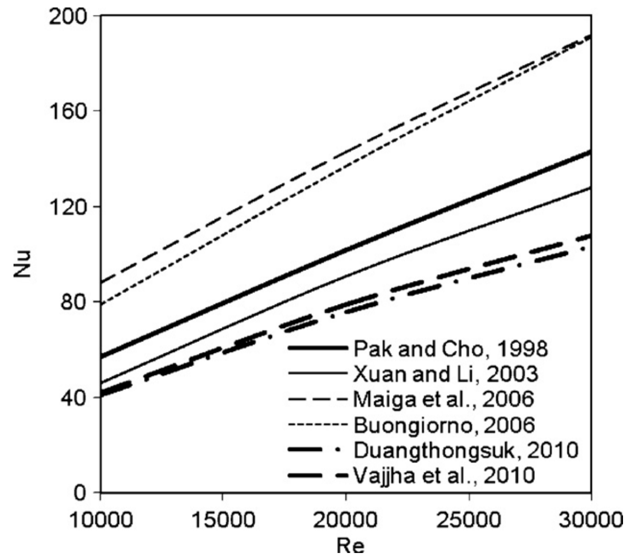


**Fig. 1.** Comparison of correlations for Turbulent flow.

where $a = 6.219 \times 10^{-3}$, $b = 1.1522$, $c = 0.1533$, $d = 2.5228$, $e = 0.57825$, $f = 0.2183$, $d_{ref} = 100$ nm, $x_+ = x/(DRePr)$.

Duangthongsuk and Wongwises [20] experimentally investigated the forced convective heat transfer and flow characteristics of a nanofluid consisting of water and 0.2–2 vol.% $TiO_2$ nanoparticles flowing in a horizontal double-tube counter flow heat exchanger under turbulent flow conditions and showed that the heat transfer coefficient of nanofluid increased with increasing the Reynolds number and particle concentrations. They proposed the following correlation for predicting the Nusselt number:

$$Nu_{nf} = 0.074Re_{nf}^{0.707}Pr_{nf}^{0.385}\phi^{0.074} \tag{20}$$

Vajjha et al. [21] experimentally investigated the forced convective heat transfer of nanofluids comprised of aluminum oxide, copper oxide and silicon dioxide dispersed in ethylene glycol and water in the fully developed turbulent regime. Based on temperature dependent rheological and the thermophysical properties of nanofluids, the following correlation was proposed for the convective heat transfer:

$$Nu_{nf} = 0.065(Re_{nf}^{0.65} - 60.22)(1 + 0.0169\phi^{0.15})Pr_{nf}^{0.542} \tag{21}$$

The summery of forced convection heat transfer correlations is given in Table 2. Comparison of the Nusselt number correlations for in-tube turbulent flow of alumina–water nanofluid is shown in Fig. 1. Particle diameter, tube diameter, volume fraction have been taken as 20 nm, 5 mm and 0.03%, respectively. The density, heat capacity have been calculated by Eqs. (2) and (3). The viscosity of nanofluid has been calculated by Einstein's equation [20], given by:

$$\mu_{nf} = (1 + 2.5\phi)\mu_{bf} \tag{22}$$

The effective thermal conductivity of nanofluid has been calculated by Yu and Choi equation [22], given by,

$$k_{nf} = \left[\frac{k_p + 2k_{bf} + 2(k_p - k_{bf})(1+n)^3\phi}{k_p + 2k_{bf} - (k_p - k_{bf})(1+n)^3\phi}\right]k_{bf} \tag{23}$$

where $n$ is the ratio of the nanolayer thickness to the particle radius, taken as 0.1.

Comparison shows that the experimental based correlations yields vary close results compared to numerical based correlations due to misleading assumptions of physical mechanisms of nanofluids in numerical study.

**Table 2**
Force convection heat transfer correlations.

| Author | Nanofluids | Conditions | *Re* range | $\phi$ (%) |
|---|---|---|---|---|
| Pak and Cho, 1998 | $Al_2O_3$–$H_2O$, $TiO_2$–$H_2O$ | Turbulent, constant heat flux | $10^4$ to $10^5$ | 0.99–2.78 |
| Li and Xuan, 2002 | Cu–$H_2O$ | Laminar, constant heat flux | ≥800 | 0.3–2.0 |
| Xuan and Li, 2003 | Cu–$H_2O$ | Turbulent, constant heat flux | 10,000–25,000 | 0.3–2.0 |
| Yang et al., 2005 | Graphite–oil | Laminar | 5–110 | ≤2.5% |
| Maïga et al., 2005 | $Al_2O_3$–$H_2O$, $Al_2O_3$–EG | Laminar | ≤1000 | ≤10% |
| Maïga et al., 2006 | $Al_2O_3$–$H_2O$ | Turbulent, constant heat flux | $10^4$ to $5\times10^5$ | 0–10 |
| Buongiorno, 2006 | NA | Turbulent | NA | NA |
| Anoop et al., 2009 | $Al_2O_3$–$H_2O$ | Laminar | 500–2000 | ≤1.8 |
| Daungthongsuk and Wongwises, 2010 | $TiO_2$–$H_2O$ | Turbulent | 3000–18,000 | 0.2–2.0 |
| Vajjha et al., 2010 | CuO, $SiO_2$, $Al_2O_3$ | Turbulent | 3000–16,000 | ≤6% (CuO, $SiO_2$) ≤10% ($Al_2O_3$) |

Fig. 2 shows the comparison of various proposed correlations for in-tube laminar flow of alumina–water nanofluid. Particle diameter, tube diameter, volume fraction have been taken as 50 nm, 4.5 mm and 1%, respectively. Properties have been calculated by the equations given above. Li and Xuan correlation [13] yields higher Nu value and Maiga et al. [16] correlation for constant wall temperature conditions yields lowest Nu value within the four correlations for developed flow. On the other hand, for developing laminar flow, the experimental results by Rea et al. [23] for vertical tube flow are in good agreement with Anoop et al. [19] correlation with minor overprediction. The large deviations of predicted values for proposed correlations may be due to following reasons: (i) strong influence of particle properties (shape, size, etc.) and nanofluid composition on flow and heat transfer charteristiecs (ii) misleading of viscosity and thermal conductivity data, (iii) lack of common understanding on basic mechanism of nanofluid flow, (iv) experimental uncertainty, and (v) insufficient experimental data for nanofluid heat transfer.

## 4. Pressure drop of nanofluids

Experimental results [12–14] showed that the pressure drop of the nanofluids fairly matches with the values predicted from conventional correlations of base fluid for both laminar and turbulent flows. Hence, the conventional fraction factor correlation can be use for pressure drop prediction. Pak and Cho [12] showed that Darcy friction factors for the dispersed fluids of the volume concentration ranging from 1% to 3% coincided well with textbook correlation for turbulent flow of a single-phase fluid. Due to the increase in the viscosity of dispersed fluids, there is an additional pumping penalty of approximately 30% at a volume concentration of 3%. Li and Xuan [13] experimentally found that the friction factors of the nanofluids coincide well with those of the water in the pressure drop and the nanofluid with the low volume fraction incurs almost no augmentation of pressure drop. The experimental study by Xuan and Li [14] implied that the friction factor correlation for the single-phase flow (base fluid) can be extended to the dilute nanofluids. Recent experimental investigation on viscous pressure loss characteristics of alumina–water and zirconia–water nanofluids in laminar flow regime by Rea et al. [23] also showed that their test results were in good agreement with prediction from conventional correlation for laminar flow. Duangthongsuk and Wongwises [20] experimentally showed that the pressure drop of nanofluids was slightly higher than the base fluid and increases with increasing the volume concentrations and proposed following correlation for friction factor:

$$f_{nf} = 0.961\phi^{0.052} Re_{nf}^{-0.375} \tag{24}$$

The friction factor correlation of nanofluid, which has been established for $Al_2O_3$, $SiO_2$ and CuO nanofluids [21], is given by,

$$f_{nf} = 0.3164 Re_{nf}^{-0.25} \left(\frac{\rho_{nf}}{\rho_w}\right)^{0.797} \left(\frac{\mu_{nf}}{\mu_w}\right)^{0.108} \tag{25}$$

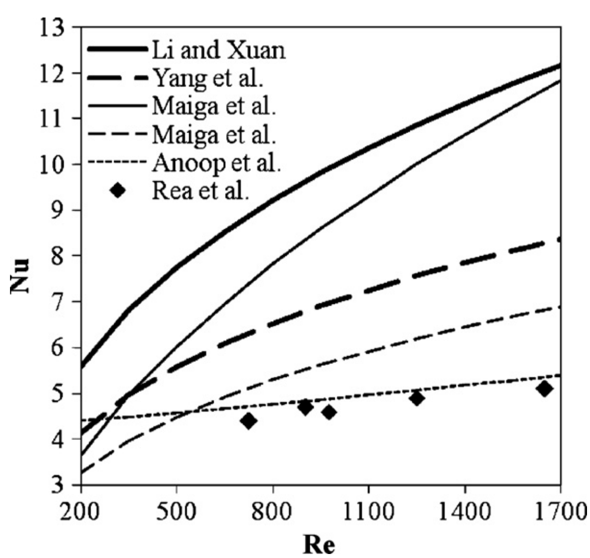


**Fig. 2.** Comparison of correlations for laminar flow.

## 5. Natural convective heat transfer of nanofluids

Ho et al. [24] have conducted an experimental study on natural convection heat transfer of an alumina–water nanofluid in vertical square enclosures of different sizes, whose dimensions, width × height × length (mm), were 25 × 25 × 60, 40 × 40 × 90, and 80 × 80 × 180, respectively. The volumetric fractions of the alumina ($Al_2O_3$) nanoparticles varied from 0.1% to 4%. The Rayleigh number varied in the range of $6.21\times10^5$ to $2.56\times10^8$. A correlation analysis based on the thermophysical properties of the nanofluid formulated showed that the heat transfer efficacy of using nanofluid for natural convection in enclosure is dependent on the net influences by the relative changes in the thermophysical properties of the nanofluid with respect to its base fluid, including the thermal conductivity, dynamic (or kinematic) viscosity, the specific heat (or heat capacity), as well as the volumetric thermal expansion coefficient. Among these thermophysical properties, only the relative increase in thermal conductivity of the nanofluid contributes beneficially to the natural convection heat transfer across the enclosure while the relative changes in the remaining properties contribute detrimentally so that replacing water by the nanofluid formulated for heat transfer enhancement across the enclosure is inferred to be generally infeasible. The experimental results for the average heat transfer rate across the three enclosures appear generally consistent with the assessment based on the changes in thermophysical properties of the nanofluid formulated, showing systematic heat transfer degradation for the nanofluids containing nanoparticles of

$\phi \geq 2$ vol.% over the entire range of the Rayleigh number considered. However, for the nanofluid containing much lower particle fraction of 0.1 vol.%, a heat transfer enhancement of around 18% compared with that of water was found to arise in the largest enclosure at sufficiently high Rayleigh number. Such enhancement cannot be explained simply based on the net influence due to relative changes in thermophysical properties of the nanofluid containing such low particle fraction, thus strongly suggesting other factors may come into play. The following correlation of average Nu has been obtained by a least-square regression analysis,

$$Nu_{nf} = CRa_{nf}^{n}\left(\frac{Pr_{nf,h}}{Pr_{nf}}\right)^{m}\left(\frac{\beta_{nf,h}}{\beta_{f}}\right)^{p} \tag{26}$$

where $C$, $m$, $n$ and $p$ are the constant [24].

Mansour et al. [25] carried out an experimental investigation to study thermally developing laminar mixed convection of $Al_2O_3$–water nanofluid inside an inclined copper tube submitted to a uniform wall heat flux at its outer surface. The effects of nanoparticles concentration and power supply on the development of the thermal field were studied and discussed under laminar flow condition. Results show that the experimental heat transfer coefficient decreases slightly with an increase of particle volume concentration from 0 to 4% for horizontal inclination and remains constant for vertical inclination. They proposed two new correlations to calculate the Nusselt number in the fully developed region for horizontal and vertical tubes, for Rayleigh number from $5 \times 10^5$ to $9.6 \times 10^5$, Reynolds number from 350 to 900 and particle volume concentrations up to 4%. Using the experimental data, the following correlation was determined for the Nusselt number in a horizontal tube as a function of the particle concentration and the Rayleigh number:

$$Nu_{nf} = Nu_0(1 - \phi^{0.625})(1 + 5.25 \times 10^{-5} Ra^{1.06})^{0.135} \tag{27}$$

For the vertical tube, a new correlation expressing the Nusselt number as a function of the Grashof and Reynolds numbers is as follows:

$$Nu_{nf} = Nu_0\left(1 + 52 \times 10^{-4}\frac{Gr}{Re}\right)^{0.28} \tag{28}$$

where $Nu_0$ is the forced convective Nusselt number.

## 6. Convective heat transfer in microchannels

Jung et al. [26] measured the convective heat transfer coefficient and friction factor of nanofluids in rectangular microchannels. Aluminum dioxide ($Al_2O_3$) with diameter of 170 nm nanofluids with various particle volume fractions were used in experiments to investigate the effect of the volume fraction of the nanoparticles to the convective heat transfer and fluid flow in microchannels. The channel aspect ratio was 150. Three channels were used with cross-sections 50 μm × 50 μm, 50 μm × 100 μm and 100 μm × 100 μm. The Reynolds number was varied up to 300. The convective heat transfer coefficient of the $Al_2O_3$ nanofluid in laminar flow regime was measured to be increased up to 32% compared to the distilled water at a volume fraction of 1.8 vol.% without major friction loss. It was found that the Nusselt number measured increases with increasing the Reynolds number in laminar flow regime. The measured Nusselt number which turned out to be less than 0.5 was successfully correlated with Reynolds number and Prandtl number based on the thermal conductivity of nanofluids. The following correlation was proposed based on the measured data of the Nusselt number for the various nanofluids of laminar flow regime in microchannels with considering the volume fraction of nanoparticles:

$$Nu_{nf} = 0.014\phi^{0.095} Re_{nf}^{0.4} Pr_{nf}^{0.6} \tag{29}$$

They investigated the friction factors for the nanofluids with several volume fractions of nanoparticles in different dimension of microchannels and showed that the measured values of the friction factor are close to the theoretical value from the correlation for the flow in microchannels, $f = 56.9/Re_D$ [27]. Minor losses at microchannel inlet and outlet were analyzed and, consequently, could be neglected at microchannel flow of pure water. It was observed that the friction factors of the tested nanofluids are close to those of water at the same Reynolds number.

## 7. Conclusions

The natural and forced convective heat transfer and pressure drop correlations for both laminar as well as turbulent flows of nanofluid are revised here. The review shows that the correlations for Nusselt number have been developed based on both experimental and theoretical studies. It may be noted that most of the correlations have been developed for spherical nanoparticle dispersions. Most of the experimental studies showed that the pressure drop of the nanofluids fairly matches with the values predicted from conventional correlations of base fluid for both laminar and turbulent flows. Hence, the conventional fraction factor correlation can be use for pressure drop prediction of nanofluid. However, the conventional correlation is not suitable for heat transfer coefficient of nanofluid and hence various correlations have been suggested for the Nusselt number for both laminar and turbulent flow. Large deviation of *Nu* has been observed between proposed correlations both for laminar and turbulent flow. This may be due to following reasons: (i) strong influence of particle properties and nanofluid composition on flow and heat transfer characteristics, (ii) misleading of viscosity and thermal conductivity data, (iii) lack of common understanding on basic mechanism of nanofluid flow, and (iv) insufficient experimental data for nanofluid heat transfer. Hence, further investigation is needed to develop a general heat transfer correlation of nanofluid.

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